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NEW CRITERIA FOR FIRE PROTECTION OF LARGE AIR FORCE WAREHOUSES

Volume II

Friction Loss in Pipes: Minimization by the Use of Chemical Additives

D. E. Breen

D. G. Goodfellow

Factory Mutual Research Corporation
Norwood, Massachusetts

TECHNICAL REPORT NO. AFWL-TR-70-1, Vol. II

August 1970

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FOREWORD

This report was prepared by the Factory Mutual Research Corporation, Norwood, Massachusetts, under Contract F29601-69-C-0070. The research was performed under Program Element 62301F, Project 5713.

Inclusive dates of research were October 1969, through April 1970. The report was submitted 1 July 1970 by the Air Force Weapons Laboratory Project Officer, Mr. James A. Mahoney (WLCT).

Information in this report is embargoed under the Department of State ITIARs. This report may be released to foreign governments by departments or agencies of the U. S. Government subject to approval of AFWL (WLCT).

This report has been reviewed and is approved.

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ABSTRACT

(Distribution Limitation Statement No. 2)

Water additive solutions were tested for relative effectiveness in reducing friction loss in turbulent flow. Polyox FRA and Separan AP 273 were judged superior in performance in a comparison of five candidate additives. A maximum increase of 2.5 in flow rate factor was attained in a simple gravity fed system. A subsequent test of Polyox FRA in a simulated sprinkler system showed no significant change in flow. This failure is believed to be due to faulty mixing. Methods to overcome this experimental difficulty are recommended.

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SECTION I

INTRODUCTION

The discovery that water soluble polymers at concentrations on the order of 25 ppm can decrease friction loss in pipes by more than 70 percent has generated considerable interest in the fire protection profession. The incentive to develop chemically induced friction reduction stems from both economic and technical reasons. The use of smaller diameter pipes for achieving the same bulk flow rate with dilute additive solutions (as compared with water alone in larger diameter pipes) indicates a potential economic benefit. Alternatively, increased sprinkler density afforded by use of these additives clearly strengthens the potential system effectiveness. It is felt that a combination of these advantages is possible in large warehouse protection.

A brief literature survey and a description of several purported mechanisms by which these additives achieve improved effectiveness has been described in an earlier FM report[1]. Much of this previously reported information need not be repeated here.

In this work emphasis has been placed on the application and performance of additives rather than on detailed mathematical interpretations of performance characteristics.

SECTION II

BACKGROUND

The percent of friction loss or drag reduction, R, is defined as

$$R = \left(\frac{f - fa}{f}\right) \times 100 \qquad (1)$$

where f and fa are the friction factors for solvent and polymer solutions respectively. It is known that R depends on

1) the molecular weight and structure of the polymer;

2) concentration of polymer;

3) Reynolds number; and

4) pipe diameter.

It is known that effective drag reducers are soluble in water, are straight chain in structure, and have molecular weights on the order of 10^6. The dependence of R on concentrations is typically linear up to R values of 70-80 percent, at which point a further increase in additive concentration is without significant effect. The more effective additives achieve this plateau at concentrations on the order of 25 wt. ppm. The Reynolds number and the diameter afford guidelines to the lower limits of flow rate where drag reduction may be expected. The Reynolds number is defined as

$$N_R = \frac{VD}{u} \qquad (2)$$

where V is the velocity, D the diameter and u the kinematic viscosity. It has been demonstrated repeatedly that drag reduction can only take place when the flow is turbulent. No known polymers produce drag reduction when the flow is laminar. For turbulent flow the Reynolds number must be greater than 2100. In addition, the smaller the diameter, the lower is the Reynolds number at which drag reduction can be observed. The point of incipient drag reduction has been characterized by assigning to it a so-called "critical Reynolds number," $N_R)_{cr}$. At this point the energy dissipation of high-frequency disturbances associated with small eddies is suppressed. The energy that would normally be lost is converted into recoverable elastic energy. This marks the onset of drag reduction. It can be shown both theoretically[2] and experimentally[3,4] that

$$N_R)_{cr} \sim D^{8/7} \qquad (3)$$

Equation (3) indicates that incipient drag reduction in a 1-in. diameter pipe at, say, $N_R \simeq 5 \times 10^3$ would not begin in a 12-in. diameter pipe until $N_R \simeq 8.6 \times 10^4$. Similarly, a pipe flow affording 70-percent drag reduction at N_{R1} and diameter D_1 would be expected to show approximately

the same reduction in a second pipe of diameter D_2 when

$$N_{R_2} \simeq N_{R_1} \quad (D_2/D_1)^{8/7}$$

This diameter dependence is not considered a detrimental limitation on a conventional sprinkler system since the Reynolds numbers associated with realistic flow rates are sufficiently high to ensure substantial drag reduction.

Figure 1 shows N_R plotted against R for several polymers and pipe diameters. It is seen that a family of curves can be generated by varying pipe diameters. The figure also shows a monotonic envelope of maximum attainable drag reduction. The envelope was derived from the equations showing friction factor dependence on N_R for the two limiting cases of fully turbulent and laminar flow (Newtonian models). It is based on the ratio of friction factor for turbulent flow to that for laminar, viz:

$$R_{max} = \left(\frac{f_T - f_L}{f_T}\right) \times 100$$

where f_T and f_L are the friction factors for turbulent and laminar flow. At the intersection of the curves describing these two types of flow (near $N_R \simeq 2100$), $f_T = f_L$ and the value of R_{max} is zero. The quantity $f_T - f_L$ increases with increasing N_R, and hence, the value of R_{max} increases. On this basis, an additive that achieved complete suppression of turbulence would attain maximum drag reduction. Measured values of f would then fall on the graph of the equation describing purely laminar flow. The "forbidden region" of Figure 1 represents an area that is theoretically and experimentally unattainable.

Two different diameter Polyox tests are shown in Figure 1. Both tests yielded data points lying on the envelope. When the drag reducing efficiency of an additive is as high as these reported values, the effect of diameter becomes less important. Indeed, the dependence may become undetectable for the smaller diameter pipes.

The experimental determination of $N_{R})_{cr}$ for a given pipe diameter also depends on concentration of the polymer and on its chemical composition. Similarly, percent drag reduction for $N_R > N_{R})_{cr}$ will also depend on these parameters. For a given pipe diameter, the percent drag reduction, beginning at zero for $N_{R})_{cr}$, increases with Reynolds number. Again a plateau effect occurs at high Reynolds numbers.

The Reynolds numbers associated with 32 heads operating at 0.3 density in an ordinary hazard sprinkler system is shown in Figure 2. This system is a representative section of a Robins Air Force Base warehouse sprinkler system. It is seen that the values of N_R associated with the various diameters are large and fall within the graphical region in Figure 1 where large drag reduction would be expected for poly(ethylene oxide) and other effective additives.

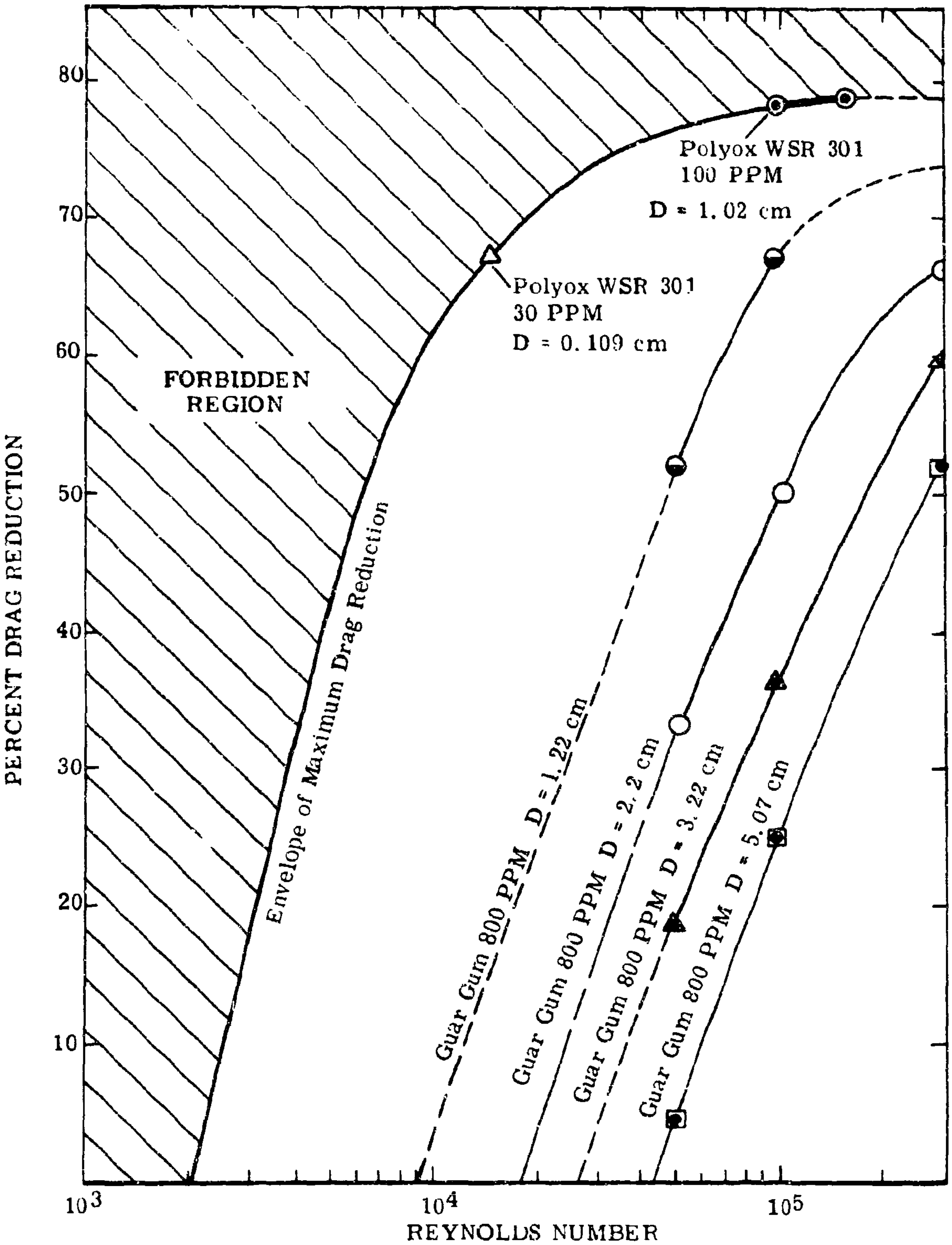

FIGURE 1 PERCENT DRAG REDUCTION VS REYNOLDS NUMBER FOR POLYOX AND GUAR GUM SOLUTIONS IN VARYING PIPE DIAMETER (REFS. 3 AND 11)

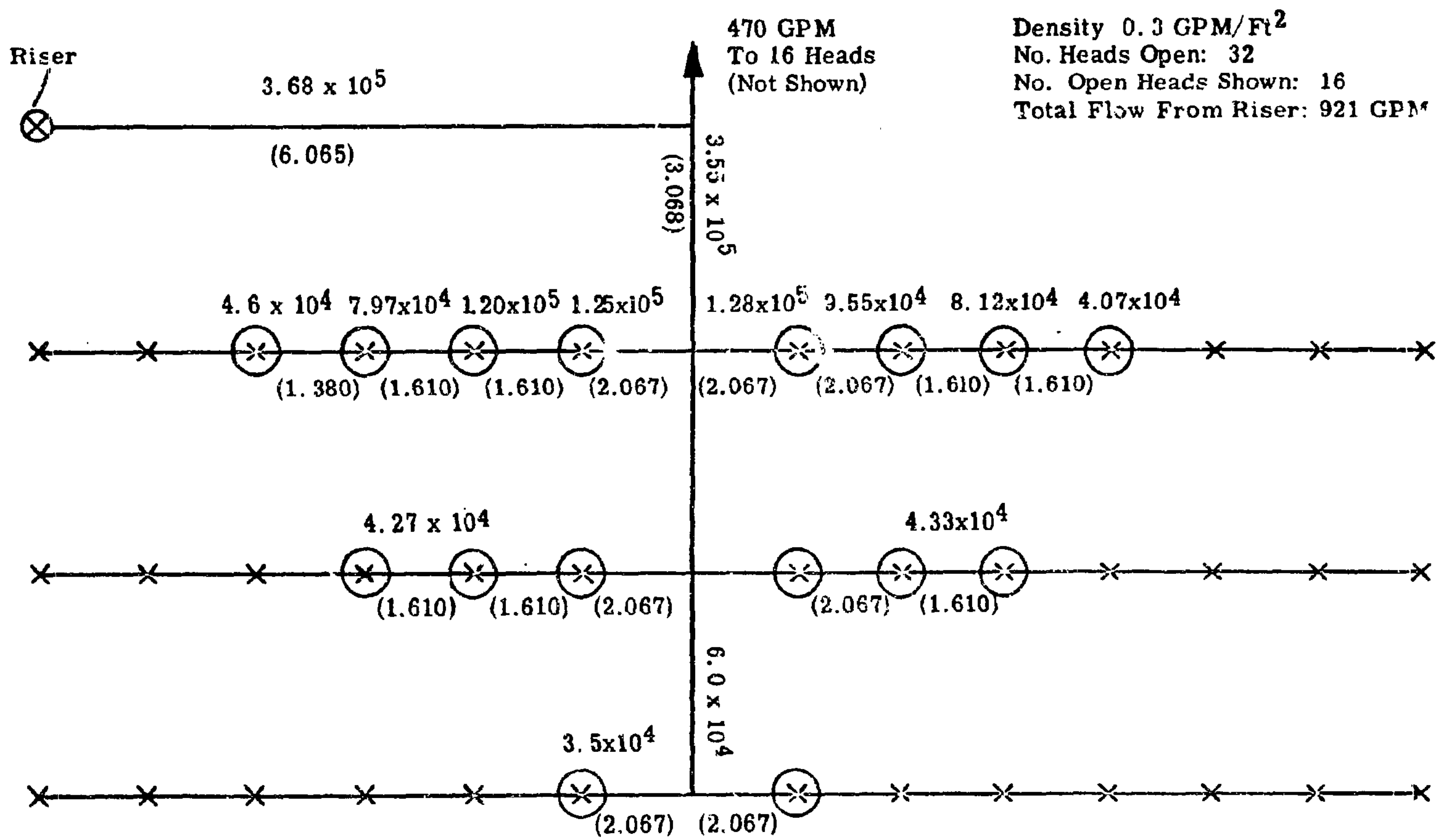

FIGURE 2 REYNOLDS NUMBERS ASSOCIATED WITH A 0.3 GPM/FT^2 DENSITY IN VARIOUS SECTIONS OF ORDINARY HAZARD PIPE SCHEDULE. OPEN HEADS ARE CIRCLED. NUMBERS IN PARENTHESIS ARE DIAMETERS IN INCHES

Calculations by the Naval Undersea Research and Development Center for the Los Angeles County Fire Department indicate that a 70-percent drag reduction will result in an 80-percent higher volume of flow through hose (5). Although essentially correct, this calculated increase is not entirely achieved in reality because the added flow causes slightly increased pressure losses within the pipe and the discharging port.

Differences in the performance of additive solutions and water as a function of elevation need not be considered because the density change of investigated chemical additives is negligible, compared to water. Losses due to elevation would be essentially equal, with or without an additive.

Introduction of an agent into the system reduces losses for the established velocity. The pressure at the port is increased by this reduction factor allowing an increased discharge rate. It follows that increasing this port velocity proportionally increases the velocity in the pipe and hence contributes to friction losses, although to an extent far less for the additive solutions than for water.

Tests carried out by the New York City Fire Department[6] have shown that 50 percent more water can be pushed through a 1-1/2 in. line on a pumper truck by using a 50 ppm Polyox proportioning device. The throw is doubled and the pump pressure is reduced 20 percent.

SECTION III

EXPERIMENTAL PROGRAM

1. ADDITIVE SCREENING

a. Test Procedure

Drag reduction measurements have been carried out on Polyox FRA, Separan AP 273, carboxymethyl cellulose (CMC), Polyhall 295, and Gantrez HY-H. The test procedure used in the screening investigation consisted of a 55-gal reservoir supplying a 22-ft section of 0.622-in. diameter test pipe by gravity feed through a 2.5-in. diameter rubber-lined hose (Figure 3). The diameter of the hose was chosen significantly larger than the test pipe to maximize pressure drop in the latter section. A differential mercury manometer and a pair of piezometer rings were used to measure the pressure drop over a 20-ft section of pipe. The upstream piezometer ring was attached approximately 2 ft from the hose/pipe junction to ensure a fully developed velocity profile. A gate valve located at this junction permitted throttling to hold the pressure drop constant and make comparative flow rate measurements.

A gravity fed system was selected in preference to a pump in order to minimize mechanical shear degradation effects which are known to decrease the effectiveness of some additives(7,8,9,10). Solutions were prepared by dissolving 2 to 20 grams of the polymer additive into 0.75 gal of water* and diluting this concentrated solution to obtain the 50 gal of feed solution. The effluent passing through the test pipe was collected over known time intervals and weighed to determine the gpm. Effluent was discarded after each run. Water was used to purge the system between polymer solution tests. Purging was maintained until the level of mercury in the differential manometer indicated the normal 27 in. for water at a hydrostatic head of 34 ft. Temperature measurements were made during the run by immersion of a 0.1°C. precision thermometer in the effluent solution. Turbulent flow was established in the range of Reynolds numbers between 3×10^4 to 8×10^4.

The volume of hose and pipe was approximately 30 pe cent of the volume of the reservoir. The polymers were mixed in the reservoir and did not penetrate to any noticeable extent into the hose and pipe space which was always occupied by water prior to testing to protect the manometer lines from air entrapment. A consequence of this experimental procedure was that approximately two minutes elapsed before the polymer solution flushed out the water and reached a steady state flow condition.

A second part of the screening program involved preliminary testing of the solubilization rates of the polymers. A simple test, designed to give approximate indication of the rates at which the various types of particulate polymeric material could dissolve in water, was made by sprinkling the polymers over the surface of equal volumes of water and observing the time to achieve visual dissolution.

*A small amount (30-50 ml) of isopropyl alcohol was used to make a slurry with the additive to facilitate dissolution.

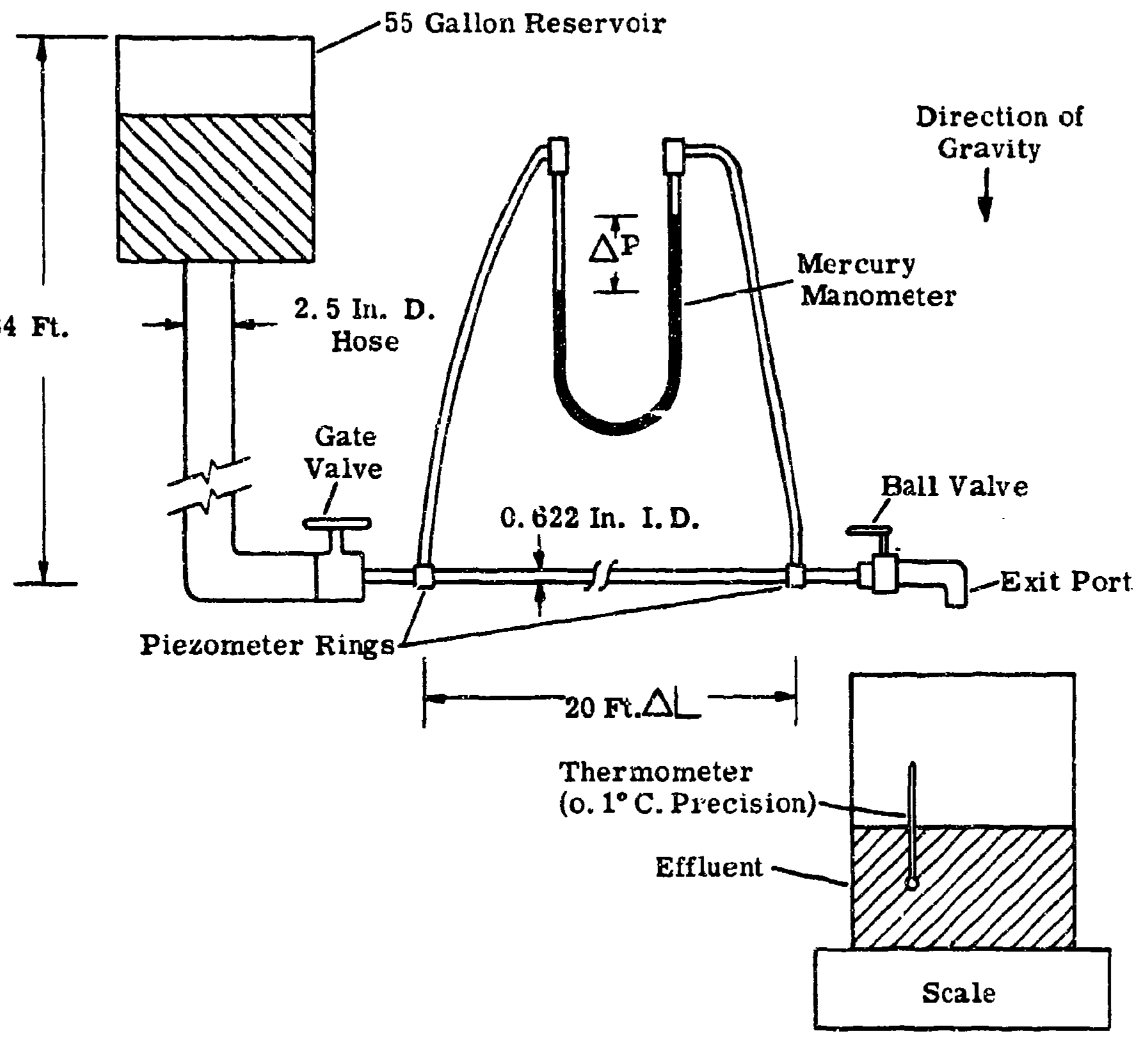

Figure 3 Hydrodynamic Drag Reduction Test Facility For Additive Screening

b. <u>Test Results</u>

The data obtained from this study showed that two classes of polymers were dramatically effective in reducing friction loss: poly(ethylene oxide) (Polyox FRA) and polyacrylamide (Separan AP 273 and Polyhall 295). On the other hand, CMC and Gantrez actually retarded the flow rate (Table I).

The concentration dependence on flow rate for four polymers is shown in Figure 4. It is seen that Polyox FRA is a more effective drag reducer at lower concentrations than is Polyhall 295. However, at 100 ppm the two curves intersect. The flow increase factor plotted on the ordinate is directly proportional to the gpm.

Although the limit of experimental error is approximately ± 5 percent, Separan AP 273 appears to be slightly more effective than Polyox FRA over the concentration range 50–100 ppm.

TABLE I

FRICTION REDUCING ADDITIVES

IN TURBULENT FLOW PIPE EXPERIMENTS

Additive	Conc (WPPM)	Δ P (in. of Hg)	gpm	$N_R \times 10^{-4}$	Gate Valve (Open or Partially Closed)	Flow Increase Factor
Polyox FRA	100	11.7	20.0	7.8	open	2.44
"	50	12.9	20.1	7.8	open	2.45
"	25	13.6	19.5	7.6	p.c.	2.38
"	10	13.1	12.5	4.9	p.c.	1.52
Polyhall 295	100	12.4	20.0	7.8	open	2.44
"	50	12.9	18.1	7.1	p.c.	2.21
"	25	12.9	14.3	5.5	p.c.	1.74
Separan AP 273	100	12.6	20.8	8.1	open	2.54
"	50	12.3	20.7	8.0	open	2.53
Gantrez HY-H	100	27.5	11.2	4.4	open	0.95
CMC 7M85	100	27.2	11.8	-	open	1.00
Water		13.0	8.2	3.2	p.c.	1.00
"		27.5	11.8	4.6	open	1.00

PIPE MATERIAL: Schedule 40 Steel, Hot Dip Galvanized
PIPE DIAMETER: 0.622 in. I.D.
DISTANCE BETWEEN PIEZOMETER RINGS: 20 ft
SOLUTION SUPPLY: Gravity Fed
TEMPERATURE OF EFFLUENT: 19.5 ± 0.5°C
$\nu = 1.06 \times 10^{-5}$ ft^2 Sec $^{-1}$

Solubilization rate tests were also made. In these tests the dissolving process was governed by the diffusion rate. The order of increasing time to dissolve was:

Gantrez HY-H < Polyhall 295 < Separan AP 273 < Polyox FRA
(most readily soluble) (least readily soluble)

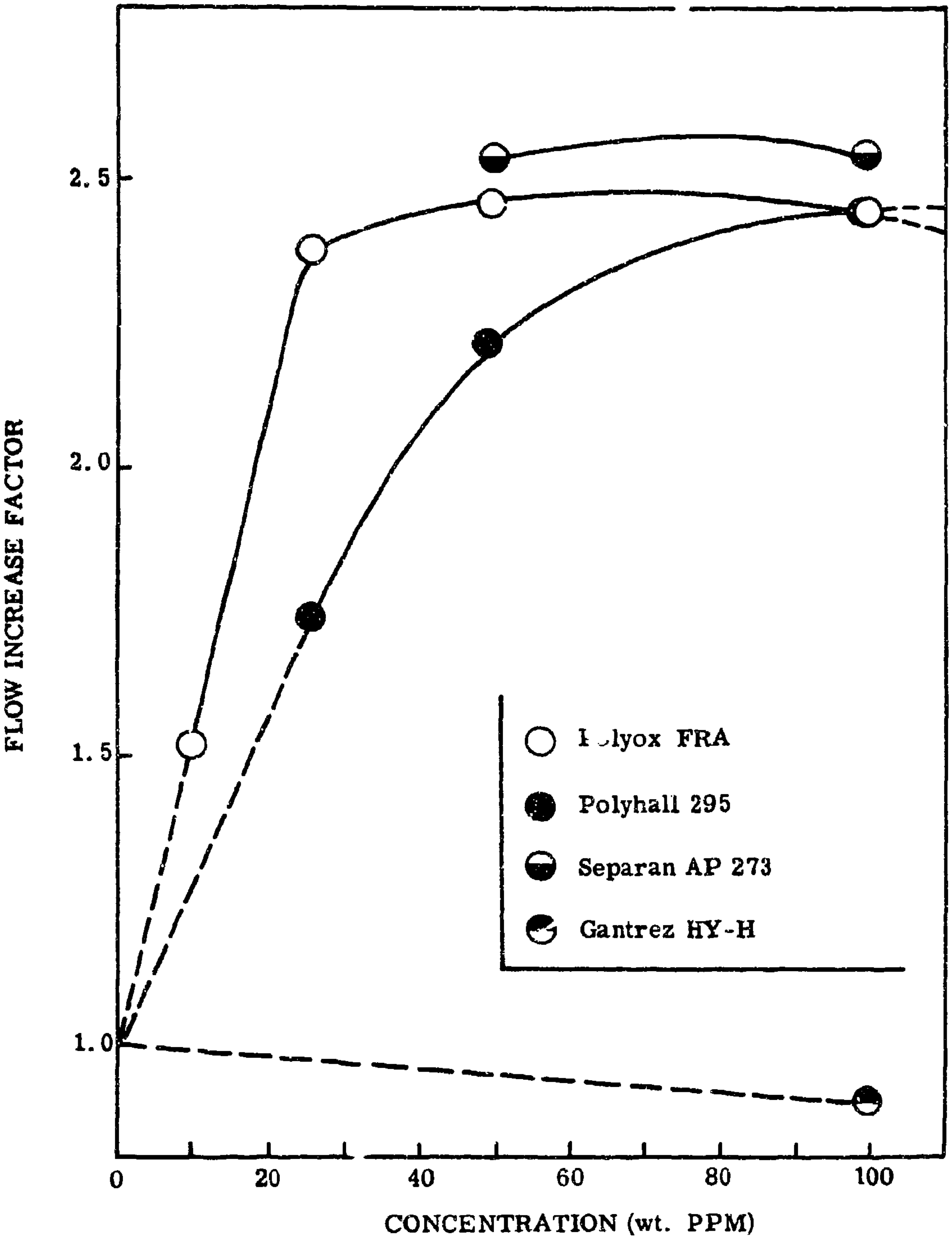

Figure 4 Concentration vs. Flow Increase Factor for Polyox FRA, Polyhall 295, Separan AP 273, and Gantrez HY-H. Differential pressure maintained at 12.6 ± 1.0 in. of mercury. ΔL = 20 ft., I.D. = 0.622 in., N_r = 3.2 - 8.1 x 10^4 (Dashed lines are extrapolations)

c. Discussion

The data show that as much as 2.5 times more water can be transported through a pipe with an additive solution when gate valve throttling is used to keep the differential pressure constant from run to run. This fact underscores the potential value of these additives for upgrading existing sprinkler systems and in reducing the cost of installing new systems.

The data obtained in these tests corroborate and extend the work done by Hoyt and Fabula[11]. The increase of 2.5 times more flow corresponds to an apparent drag reduction of 83 $\pm$ 4 percent. This reduction is due predominantly to the presence of the additive (Polyox FRA or Separan AP 273), although a small fraction can be attributed to the decrease in friction factor which invariably occurs with increasing Reynolds number. Our calculations show that the maximum true drag reduction, afforded by the additive alone, is actually 80 $\pm$ 4 percent. This percentage, if plotted on Figure 1, would lie on or close to the envelope of maximum attainable drag reduction at $N_R = 8 \times 10^4$.

The data presented in Figure 4 show that Polyox FRA, Separan AP 273 and Polyhall 295 are effective drag reducers. The general behavior of these compounds is similar: the lower concentrations (0-50 ppm) afford steep increases in drag reduction with increasing concentration, whereas at 50-100 ppm a plateau effect occurs.

Polyhall 295 shows the interesting property of being only 50 percent as effective as Polyox FRA at 25 ppm, but equally effective at 100 ppm. At this concentration it appears to have reached a plateau in the flow increase factor which is close to the maximum flow increase factors of the other polymers, i.e., 2.5.

Gantrez HY-H and CMC 7M85 showed a modest decrease in flow factor at 100 ppm (Table I). This retardation may be attributable to low molecular weight. It is known that poly(ethylene oxide), for example, is ineffective at molecular weights below 300,000, even at high Reynolds numbers.

The solubilization rate measurements showed that Gantrez went into solution more rapidly than the other polymers. Relatively rapid solubilization is generally found in low molecular weight compounds and is certainly a possible explanation for the retardation.

Ideally, it would be most convenient if the more effective additives could be solubilized as rapidly as, say, sugar dissolving in water. The dissolution rate can, of course, be increased markedly by using suitable slurry vehicles. Isopropyl alcohol was used as such a vehicle in these flow experiments. Other materials such as polyvinylpyrrolidone and polypropylene glycol have been used successfully by others[5] to facilitate dissolution.

2. SIMULATED SPRINKLER SYSTEM

a. Test Procedure

An experiment was designed to accumulate comparative data for water and a friction reducing solution using a comparatively simple sprinkler system. Based on results of experiments in III-1, poly(ethylene oxide), i.e., Polyox FRA, was used as the additive. Specific measurements included the pressure loss through a section of pipe, the discharge coefficient of an automatic sprinkler nozzle, sprinkler distribution, and drop size of sprinkler discharge.

The experimental setup consisted of a 10-ft. length of nominal one-in. diameter, schedule 40 pipe discharging through a pendent Viking Type C sprinkler suspended above a horizontal turntable (See Figure 5). This rotating table technique determined the average radial density. Water was supplied from a centrifugal pump, and its discharge pressure was established by regulating the rate of discharge through a by-pass. Velocity through the test section was measured with a Fisher and Porter Flowrator and controlled by a downstream valve. A weigh barrel acted as a check on the accuracy of the flow meter.

Additive proportioning was achieved by maintaining a constant-pressure air cushion on a reservoir and controlling the rate of injection by manipulating a needle valve. A liquid level indicator on the reservoir acted as a check on proportioning accuracy. A differential manometer measured the pressure drop over the test section of pipe, and a mercury manometer measured the pressure maintained at the discharging sprinkler nozzle. Drop size measurements were made using the FMRC freezing technique. The FRA solution was prepared by dissolving 125 grams of Polyox FRA into 50 gallons of water. A small amount of isopropyl alcohol was used to make a slurry with the additive to facilitate dissolution.

A series of tests with water were made for several flow rates. Three tests under the same flow conditions were made to assure reproducibility. Specific flows were repeated with the Polyox FRA solution injected. A rate of approximately 100 ppm assured a concentration in excess of requirements needed to attain maximum drag reduction.

b. Test Results

No significant drag reduction was observed with the discharge rate maintained constant. (< 4 percent) The contrast between the first experiments (and work performed by other investigators) and this second trial is striking. We believe the design of the experiment introduced numerous parameters for which there exists no prior experience. A further experimental investigation is needed to isolate specific parameters so as to ascertain their individual effects.

The radial distribution patterns of water and FRA solutions are shown in Figure 6. Both distributions lie above the minimum acceptable curve. The FRA solution affords a slightly higher density than water at distances greater than 5 feet. Slight foaming was observed in the FRA solution runoff.

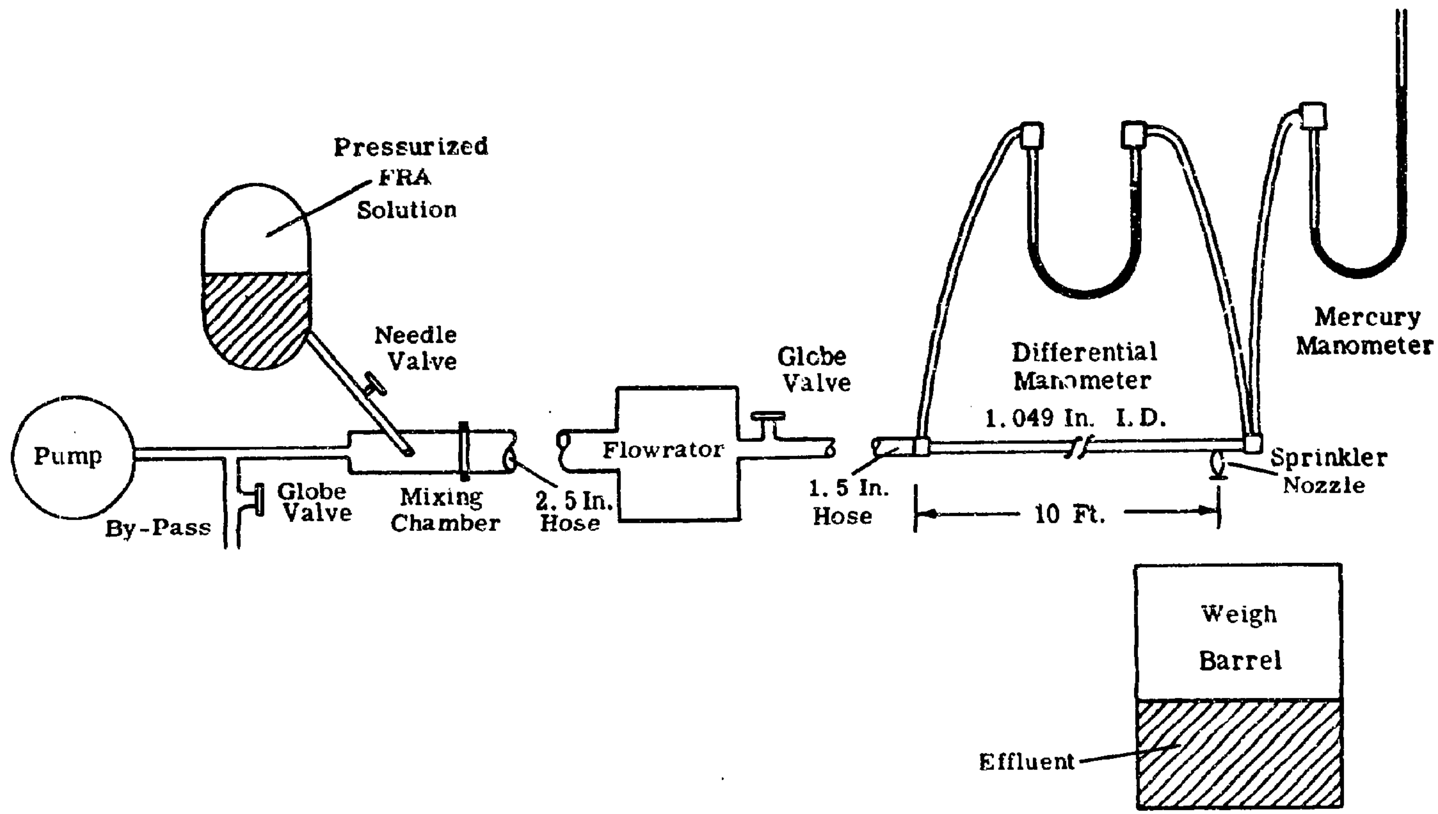

FIGURE 5 SIMULATED SPRINKLER SYSTEM

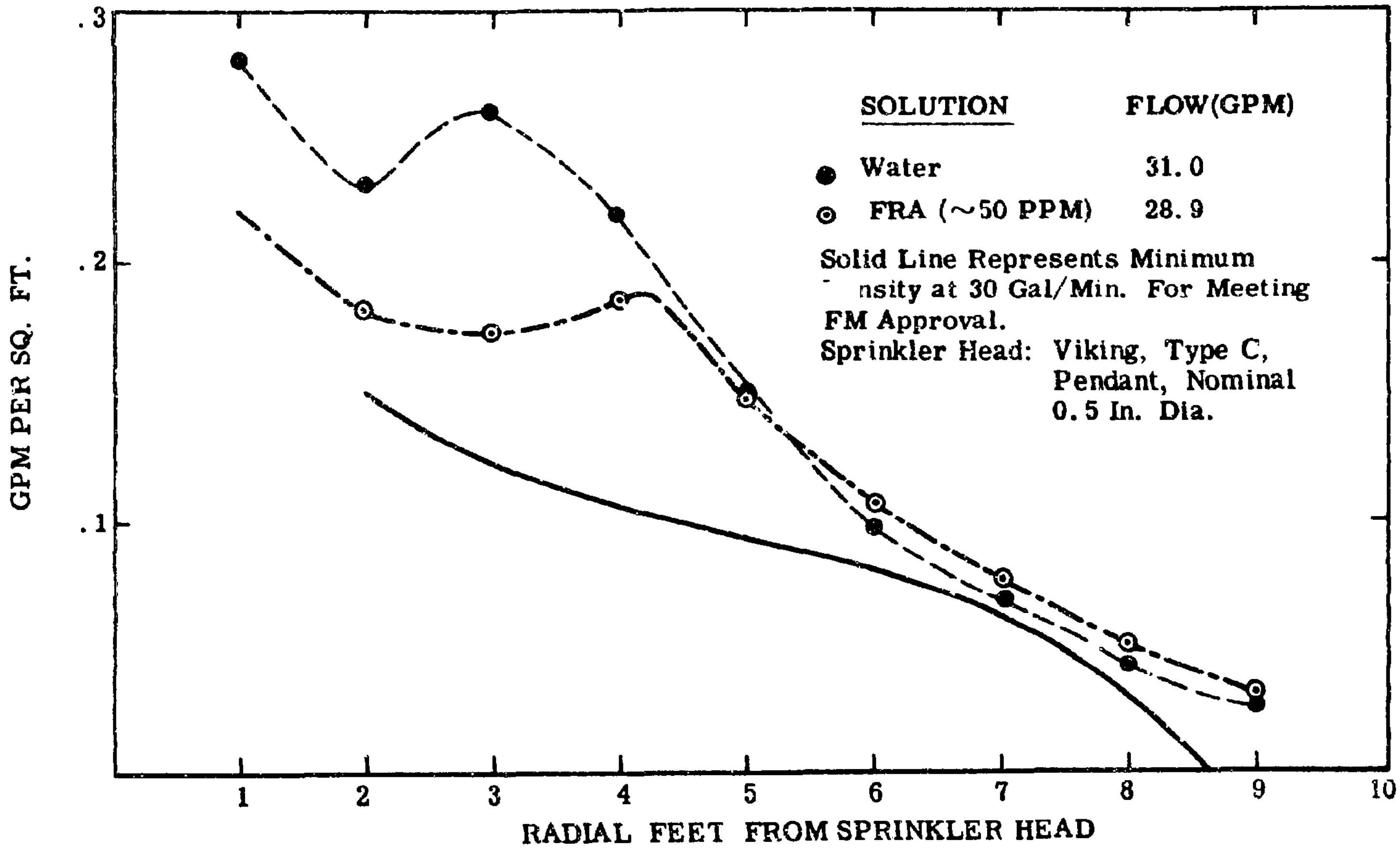

FIGURE 6 RADIAL DISTRIBUTION DENSITY OF WATER AND FRA SOLUTION

The method used to prepare or inject the FRA concentrate caused entrapment of many small air bubbles. It was evident at the Flowrator that the air remained in suspension; the solution had the appearance of carbonated water. This definitely had an adverse effect on the drag reduction results and was also evident in the drop size measurements, i.e., some of the collected drops had hollow centers. Precise interpretation of data concerning the effect of Polyox FRA on drop size is, therefore, not available from present data.

c. Discussion

The simple gravity fed system described in III-1 has demonstrated the drag reducing ability of selected polymers. The pump system, tested subsequently, did not show a significant change in flow or pressure. It is believed that inadequate mixing was responsible for this unexpected behavior. The polymer concentrate contained approximately 550 wt. ppm of polymer which was injected by pressure into the core of the pipe flow to give a concentration of 50-100 ppm. Complete mixing may not have occurred during the transit time of approximately 38 seconds (time from injection site to sprinkler head). It is known that the solution/pipe interface or boundary layer is an important parameter in drag reduction and that failure to achieve mixing in this region would have a defeating effect on anticipated drag reduction.

Inadequate mixing within the boundary layer region is considered the most probable explanation of the simulated sprinkler system results. No such mixing problems or absence of drag reduction were encountered in the gravity fed system since all solutions were pre-mixed to the desired concentration.

Calculations show that a 30-gpm flow rate in the nominal 1-in. diameter pipe corresponds to a Reynolds number of 7×10^4. This value is sufficiently large to insure a significant percent drag reduction based on available data for similar pipe diameters (Figure 1).

An accurate estimate of the maximum attainable drag reduction that might have been reached in this part of the test program is not currently available due to a paucity of published experimental work on Polyox FRA solutions in 1-in. diameter pipes. Needed for this calculation is a value for $N_R)_{cr}$ and the dependence of R on N_R over a graphical span of at least 1 decade for this particular grade of polymer. Rough estimates indicate that 50-60 percent drag reduction should have been achieved in our experimental arrangement.

SECTION IV

RECOMMENDATIONS

1. Resolve the apparent problems of the experimental design of the simulated sprinkler system by isolating and testing individual components.

   a. The first consideration should be to override the present injection method and substitute a premixed DRA solution.

   b. Following success in (a), further attempts at improved mixing should be made, e.g., injection at the boundary layer and/or insertion of an eddy plate downstream of the injection point.

2. With the experimental setup operating satisfactorily, confirmation should be made of drag reduction, radial density patterns, and drop size distributions.

3. Evaluations should be made of additives other than Polyox (e.g., Polyhall 295, Separan AP 273). This would include molecular weight determinations by intrinsic viscometry.

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13. ABSTRACT

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Fire detection						
Fire research						
Sprinkler systems (upgrading)						
Water additive systems						
Air Force Warehouse (Fuels and Hazards)						
Friction reducers						